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CASE REPORT

# Effects of aggregating forests, establishing forest road networks, and mechanization on operational efficiency and costs in a mountainous region in Japan

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**Abstract:** We investigated forest road networks and forestry operations before and after mechanization on aggregated forestry operation sites. We developed equations to estimate densities of road networks with average slope angles, operational efficiency of bunching operations with road network density, and average forwarding distances with operation site areas. Subsequently, we analyzed the effects of aggregating forests, establishing forest road networks, and mechanization on operational efficiency and costs. Six ha proved to be an appropriate operation site area with minimum operation expenses. The operation site areas of the forest owners' cooperative in this region aggregated approximately 6 ha and the cooperative conducted forestry operations on aggregated sites. Therefore, 6 ha would be an appropriate operation site area in this region. Regarding road network density, higher-density road networks increased operational expenses due to the higher direct operational expenses of strip road establishment. Therefore, road network density should be reduced to approximately 200 m·ha$^{-1}$ within average pre-yarding distances on which a grapple loader could conduct bunching without winching. With larger stem volumes a larger reduction in operational expenses occurred for the mechanized operation system compared to the conventional operation system. However, with smaller stem volumes, the operational expenses for the mechanized operation system were higher than for the conventional operation system. Therefore, the appropriate operation system and machine sizes should be determined based on stem volumes.

**Keywords:** aggregating forests; establishing forest road networks; mechanization; operational efficiency; costs



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## Introduction

The labor productivity of Japanese log production has been improving since the 1970s, reaching 4.00 m$^3$/person-day in clear-cutting operations and 3.45 m$^3$/person-day in thinning operations in 2008 (Forestry Agency 2009). However, these figures are much lower than those in Europe, particularly Sweden, where the labor productivity of forestry is approximately 24 m$^3$/person-day. Forest ownership in Japan is characterized by a large number of small, fragmented, and scattered forest stands. The small forest owners tend to be reluctant to adopt modern forestry practices due to low profitability. The scale of private forestry contractors is also relatively small. The small forestry contractors use small forestry machines on small forestry operation sites, resulting in lower annual production and lower profitability.

To overcome these problems, the Japan Forest Agency implemented a measure on "coordination and consolidation of forestry practices." This measure will ensure coordination among a number of small forest owners and expand forestry operation sites while merging small forests. Forest road networks will be established and mechanization will be promoted in order to conduct forestry operations efficiently on a large scale and reduce costs. Private forestry contractors or forest owners' cooperatives will emerge and propose a consolidated harvesting plan to forest owners who have lost interest in forest management.

The Nasu-machi forest owners' cooperative in Tochigi prefecture, Japan has been using a consolidated harvesting plan since 2009. Forest road networks have been established and mechanization has been promoted on aggregated forestry operation sites. In this study, we investigated forest road networks and forestry operations before and after mechanization on aggregated forestry operation sites. Subsequently, we analyzed the effects of aggregating forests, establishing forest road networks, and mechanization on operational efficiency and costs.

## Materials and methods

### Study site

Investigations were conducted at Azusa A and B and Nakanosawa, where forestry operations were conducted using a conventional operation system, and Kurotasawa, Shiroyama, Kawanakako, and Yanome, where forestry operations were conducted using a mechanized operation system (Table 1). The conventional operation system included chainsaw (Husqvarna 357XPC, 56.5 cc) felling and processing, mini-grapple loader (CAT 313, bucket capacity 0.14 $m^3$ with Iwafuji GS40LHV) bunching, and mini-forwarder (Oikawa RM8HWD-AS, loading capacity 2,000 kg) forwarding (Fig. 1). The mechanized operation system included chainsaw (Husqvarna 357XPC, 56.5 cc) felling, grapple loader (Hitachi ZAXIS120, bucket capacity 0.45 $m^3$ with Iwafuji GS90LJV) bunching, processor (Hitachi ZAXIS135, bucket capacity 0.45 $m^3$ with Iwafuji GP-35A) processing, and forwarder (Morooka MST-600VDL, loading capacity 2,800 kg) forwarding (Fig. 2). Strip road networks were established as 2.0 m in width with a mini-backhoe (CAT E70B, bucket capacity 0.25 $m^3$) for the conventional operation system and 3.5 m in width with a backhoe (Hitachi ZAXIS120, bucket capacity 0.45 $m^3$) for the mechanized operation system.

The elevations of these sites ranged between 200 m and 300 m. Average annual precipitation was 1,951 mm, and maximum snow depth was 38 cm. The investigated sites were aggregated sites; however, most areas were less than 10 ha, excluding Kurotasawa and Yanome, which were both forestry operation sites with mechanized operation systems, each being more than 25 ha (Table 1). Azusa A, Kurotasawa, Shiroyama and Yanome were mixed plantation forests consisting of Japanese cedar and cypress. Azusa B and Kawanakako had Japanese cedar and Nakanosawa had Japanese cypress. The stands were approximately 50 years old, however, some forests included some young stands. The slope angles were approximately 20 degrees except at two operation sites, Nakanosawa and Yanome, that had relatively gentle slopes of approximately 10 degrees.

### Forest road network analysis

We analyzed forest road networks by density, average pre-yarding distance, ratio of average pre-yarding distance to theoretical average pre-yarding distance, average forwarding distance and $\alpha$ index (Table 2). Theoretical pre-yarding distances were estimated using a rectangular model (theoretical average pre-yarding distance = 2,500/road density). $\alpha$ indexes were the ratios of the number of actual circular road networks to the number of theoretical circular road networks, estimated using the following equation (Ono et al. 1991).

$$\alpha = \frac{\mu}{2n-5} \tag{1}$$

where, $\mu$ is the number of actual circular road networks and $n$ is the number of nodes.

**Fig. 1 Conventional operation system with chainsaw felling and processing (left), mini-grapple loader loading to mini-forwarder (middle), and truck unloading from forwarder (right)**

**Fig. 2 Mechanized operation system with grapple-loader bunching (left), processor processing (middle), and forwarder forwarding (right)**

**Table 1. Investigations of study sites**

| Operation system | Site | Species | Area (ha) | Slope angle (°) | DBH (cm) | Tree height (m) | Stem volume ($m^3$/stem) | Stand density (stem/ha) | Stock ($m^3 \cdot ha^{-1}$) | Stem thinning rate(%) | Production volume ($m^3 \cdot ha^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Conventional system | Azusa A | Japanese cedar<br>Japanese cypress | 8.6 | 25.04 | 20 | 27 | 0.56 | 1,200 | 672 | 33.4 | 75 |
| | Azusa B | Japanese cedar | 3.91 | 22.78 | 28 | 37 | 1.42 | 950 | 1,349 | 31.6 | 66 |
| | Nakanosawa | Japanese cypress | 3.03 | 8.57 | 18 | 21 | 0.32 | 1,550 | 496 | 35.4 | 87 |
| Mechanized system | Kurotasawa | Japanese cedar<br>Japanese cypress | 26.74 | 21.53 | 25 | 28 | 0.79 | 1,240 | 980 | 33.3 | 141 |
| | Shiroyama | Japanese cedar<br>Japanese cypress | 7.12 | 17.87 | 20 | 30 | 0.71 | 1,000 | 710 | 30 | 85 |
| | Kawanakako | Japanese cedar | 6.7 | 22.52 | 22 | 25 | 0.62 | 1,000 | 620 | 35 | 45 |
| | Yanome | Japanese cedar<br>Japanese cypress | 27.12 | 10.43 | 20 | 26 | 0.57 | 1,000 | 570 | 30 | 61 |

**Table 2. Forest road network analysis**

| Operation system | Site | Length (m) | Density (m/ha) | Strip road length (m) | Strip road density (m/ha) | Pre-yarding distance (m) | Raio of pre-yarding distance* | Forwarding distance (m) | Number of circular networks | $\alpha$ index (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Conventional system | Azusa A | 1,865 | 216.86 | 1,865 | 216.86 | 19.47 | 1.69 | 237.15 | 2 | 4.26 |
| | Azusa B | 807 | 206.39 | 807 | 206.39 | 18.93 | 1.56 | 134.27 | 0 | 0.00 |
| | Nakanosawa | 869 | 286.80 | 869 | 286.80 | 12.88 | 1.48 | 77.76 | 2 | 7.41 |
| Mechanized system | Kurotasawa | 6,589 | 246.41 | 5,942 | 222.20 | 23.59 | 2.32 | 356.23 | 5 | 4.42 |
| | Shiroyama | 2,138 | 300.28 | 1,877 | 263.64 | 12.82 | 1.54 | 154.73 | 1 | 1.75 |
| | Kawanakako | 1,539 | 229.65 | 952 | 142.05 | 27.74 | 2.55 | 111.98 | 2 | 6.06 |
| | Yanome | 7,718 | 284.64 | 7,718 | 284.64 | 14.57 | 1.66 | 477.43 | 11 | 4.68 |

* Ratio of average pre-yarding distance to theoretical average pre-yarding distance estimated using a rectangular model (theoretical average pre-yarding distance = 2,500/road density)

Operational efficiency and economic balances

Operational efficiency was estimated with labor inputs from operators' daily reports and production volumes from product sales reports. The direct operational expenses were estimated with operational efficiency and hourly operation costs consisting of labor and machinery expenses (maintenance, management, depreciation, and fuel and oil expenses). Labor expenses were set at 25.50 USD·$h^{-1}$. For the conventional operation system, machinery expenses were 4.19 USD·$h^{-1}$ for a chainsaw, 13.02 USD·$h^{-1}$ for a mini-grapple loader, 8.33 USD/hour for a mini-forwarder, and 21.43 USD·$h^{-1}$ for a mini-backhoe. For the mechanized operation system, machinery expenses were 43.80 USD/hour for a grapple loader, 52.20 USD·$h^{-1}$ for a processor, 35.28 USD·$h^{-1}$ for a forwarder and 47.43 USD·$h^{-1}$ for a backhoe (Nakahata et al. 2011).

Overhead costs, log transportation expenses, machine transportation expenses, handling fees associated with the forest owners' cooperative and log markets, and piling fees at the log market were considered indirect operational expenses (Zenkoku Ringyo Kairyo Fukyu Kyokai 2001). Overhead costs were estimated as 18.4% of direct operational expenses. Logs were sold to four locations: a log market, sawmill, laminated lumber factory, and chip factory. Log transportation expenses were 13.00 USD·$m^{-3}$ for the log market and the sawmill, and 15.00 USD·$m^{-3}$ for the chip factory. Logs for laminated lumber were sold at a landing and no transportation costs were incurred. Machine transportation expenses were estimated as unit costs of 50.00 USD/machine multiplied by the number of machines: four machines, including two mini-grapple loaders, for the conventional operation system, and five machines, including two forwarders, for the mechanized operation system. Handling fees associated with the forest owners' cooperative were 5% of revenues and those associated with the log market were 5% of timber prices at the log market. Piling fees at the log market were 7.00 USD·$m^{-3}$.

Revenues were estimated using production volumes and unit prices from product sales reports. For thinning operations, subsidies were received in Japan. Subsidies were estimated using standard unit price, area, assessment coefficient, and the subsidy rate of the Tochigi Prefectural Government (2010). Standard unit prices were determined by age and thinning rate. Standard unit prices with a 30% thinning rate were 5,968.33 USD·$ha^{-1}$ for a stand between 26 and 35 years old, 6,006.12 USD·$ha^{-1}$ for a stand between 36 and 39 years old, 5,719.35 USD·$ha^{-1}$ for a stand between 40 and 45 years old, and 5,792.61 USD·$ha^{-1}$ for a stand between 45 and 59 years old. The assessment coefficient and the subsidy rate were assumed to be 1.7 and 4/10, respec-

tively.

The forestry operation sites in Japan that received subsidies for thinning operations, also received subsidies for strip road establishment. Subsidies were also estimated using standard unit price, road length, assessment coefficient, and the subsidy rate of the Tochigi Prefectural Government (2010). The standard unit prices for strip road establishment were determined based on average slope angle and road width. The standard unit prices for the conventional operation system were 0.59 USD·m$^{-1}$ between 5° and 10°, 0.88 USD·m$^{-1}$ between 10° and 15°, 1.34 USD·m$^{-1}$ between 15° and 20°, 2.01 USD·m$^{-1}$ between 20° and 25°, and 2.16 USD·m$^{-1}$ between 25° and 30°. The standard unit prices for the mechanized operation system were 2.34 USD·m$^{-1}$ between 5° and 10°, 2.81 USD·m$^{-1}$ between 10° and 15°, 3.38 USD·m$^{-1}$ between 15° and 20°, 4.06 USD·m$^{-1}$ between 20° and 25°, and 7.01 USD/m between 25° and 30°. The assessment coefficient and the subsidy rate were assumed to be 1.7 and 4/10, respectively.

## Results

### Forest road network analysis

In terms of the relationship between road network density $d$ (m·ha$^{-1}$) and average slope angle $\theta$ (°), road network density decreased according to the increased average slope angle because it is more difficult to establish forest road networks on steeper terrain (Table 2).

$$d = -4.66\theta + 338.59 \tag{2}$$

On the other hand, average pre-yarding distance increased according to the increased average slope angle because average pre-yarding distance is negatively correlated with road network density (Table 2). Furthermore, forest road networks had more detours on steeper terrain. Thus, the ratios of average pre-yarding distance to theoretical average pre-yarding distance estimated using road network density also increased according to the increased average slope angle (Table 2). A longer pre-yarding distance would increase the costs of grapple loader bunching operations on steeper terrain. The average forwarding distance $L_F$ (m) increased according to the increased operation site area $A$ (ha) (Table 2).

$$L_F = 13.29A + 63.43 \tag{3}$$

Then, a longer forwarding distance would increase the costs of using a forwarder in larger areas.

The number of circular road networks increased according to the increased operation site area. However, $\alpha$ index was not as strongly correlated with the operation site area as with the average slope angle because connectivity was limited by steeper terrain (Table 2). In the forest road network analyses, differences could not be found between conventional and mechanized operation systems. This was because the forest road networks used by sites with the mechanized operation system were based on networks established in the previous thinning operations using the conventional operation system, by extending the width of the roads from 2.0 m to 3.5 m to enable the introduction of large forestry machines.

### Operational efficiency

Labor inputs and production volumes are listed in Tables 3 and 4. Higher production volume requires higher labor input. According to the labor input for each operation, longer strip roads required higher labor input for strip road establishment and higher production volume required higher labor inputs for other operations.

Operational efficiency is listed in Table 5. Mechanization improved operational efficiency. Larger stem volume, larger area and higher production volume tended to create higher operational efficiency. However, higher production volume per area created lower operational efficiency in the conventional operation system, whereas it created higher operational efficiency in the mechanized operation system. This difference occurred because mechanized operations were conducted efficiently with higher production volume per area, whereas it was difficult to conduct conventional operations, especially chainsaw processing or mini-grapple loader bunching, efficiently in forests with more felled trees and bucked logs.

**Table 3. Labor inputs (person-days)**

| | Site | Strip road establishment | Felling and processing | Bunching | Forwarding | Operation system |
|---|---|---|---|---|---|---|
| Conventional system | Azusa A | 17.5 | 92.8 | 49.0 | 68.5 | 227.8 |
| | Azusa B | 4.5 | 39.2 | 15.9 | 7.6 | 67.2 |
| | Nakanosawa | 12.0 | 77.2 | 15.0 | 12.7 | 116.8 |
| Mechanized system | Kurotasawa | 47.0 | 404.6 | 114.6 | 119.1 | 715.3 |
| | Shiroyama | 19.5 | 75.2 | 19.5 | 20.8 | 135.0 |
| | Kawanakako | 5.5 | 46.1 | 11.3 | 10.8 | 73.7 |
| | Yanome | 39.0 | 262.3 | 62.7 | 60.0 | 424.0 |

**Table 4. Revenues**

| | Site | Total volume ($m^3$) | Total revenues (USD) | Average unit price (USD/$m^3$) |
|---|---|---|---|---|
| Conventional system | Azusa A | 644.08 | 56,531.38 | 87.77 |
| | Azusa B | 258.08 | 35,549.18 | 137.75 |
| | Nakanosawa | 264.14 | 44,744.86 | 169.40 |
| Mechanized system | Kurotasawa | 3,780.62 | 350,584.95 | 92.73 |
| | Shiroyama | 606.97 | 75,213.49 | 123.92 |
| | Kawanakako | 311.08 | 33,457.97 | 107.55 |
| | Yanome | 1,658.26 | 146,852.39 | 88.56 |

The operational efficiency of strip road establishment was 106.57 m/person-day for Azusa A, 179.33 m/person-day for Azusa B, 72.42 m/person-day for Nakanosawa, 118.95 m/person-day for Kurotasawa, 96.26 m/person-day for Shiroyama, 173.05 m/person-day for Kawanakako, and 197.91 m/person-day for Yanome. Significant differences between conventional and mechanized operation systems or along average

slope angles could not be observed in these data. However, operational efficiency was negatively correlated with stand density because of stump removal. The operational efficiency of other operations in the mechanized operation system tended to be higher than in the conventional operation system; in particular, the operational efficiency of bunching in the mechanized operation system was significantly higher than in the conventional operation system. The operational efficiency of forwarding operations was expected to be reduced according to the increased average forwarding distance, but was not strongly correlated with average forwarding distance in this study.

**Table 5. Operational efficiency ($m^3$/person-day)**

| | Site | Strip road establishment | Felling and processing | Bunching | Forwarding | Operation system |
|---|---|---|---|---|---|---|
| Conventional system | Azusa A | 36.80 | 6.94 | 13.14 | 9.40 | 2.61 |
| | Azusa B | 57.35 | 6.58 | 16.23 | 33.96 | 3.84 |
| | Nakanosawa | 22.01 | 3.42 | 17.61 | 20.88 | 2.26 |
| Mechanized system | Kurotasawa | 80.52 | 9.34 | 26.15 | 31.74 | 5.29 |
| | Shiroyama | 31.13 | 8.07 | 31.13 | 29.18 | 4.50 |
| | Kawanakako | 56.56 | 6.75 | 27.53 | 28.80 | 4.22 |
| | Yanome | 42.52 | 6.32 | 26.45 | 27.64 | 3.91 |

Operational expenses

Direct operational expenses are listed in Table 6. The direct operational expenses of the mechanized operation system tended to be lower than those of the conventional operation system. Larger stem volume, larger area and higher production volume tended to increase operational efficiency and lower direct operational expenses.

**Table 6. Direct operational expenses (USD/$m^3$)**

| | Site | Strip road establishment | Felling and processing | Bunching | Forwarding | Operation system |
|---|---|---|---|---|---|---|
| Conventional system | Azusa A | 7.65 | 25.66 | 17.58 | 38.20 | 89.09 |
| | Azusa B | 4.91 | 27.06 | 14.24 | 10.58 | 56.78 |
| | Nakanosawa | 12.79 | 52.03 | 13.12 | 17.20 | 95.12 |
| Mechanized system | Kurotasawa | 5.43 | 22.50 | 15.90 | 11.49 | 55.32 |
| | Shiroyama | 14.06 | 29.33 | 13.36 | 12.50 | 69.24 |
| | Kawanakako | 7.74 | 39.36 | 15.10 | 12.66 | 74.86 |
| | Yanome | 10.29 | 36.69 | 14.22 | 13.20 | 74.39 |

The direct operational expenses of strip road establishment wer higher in Nakanosawa (for conventional operations) and in Shiroyama (for mechanized operations) (Table 6). The direct operational expenses of strip road establishment were negatively correlated with average slope angle, because a steeper average slope angle caused lower road network density. However, significant correlation was not observed between average slope angle and direct operational expenses of strip road establishment in terms of length: 2.64 USD·$m^{-1}$ for Azusa A, 1.57 USD·$m^{-1}$ for Azusa B, 3.89 USD·$m^{-1}$ for Nakanosawa, 3.46 USD·$m^{-1}$ for Kurotasawa, 4.55 USD·$m^{-1}$ for Shiroyama, 2.53 USD·$m^{-1}$ for Kawanako, and 2.21 USD·$m^{-1}$ for Yanome.

The operational efficiency of felling and processing operations in the mechanized operation system tended to be higher than in the conventional operation system. However, the direct operational expenses of felling and processing in the mechanized operation system tended to be higher than in the conventional operation system because the machinery expenses for processors were significantly higher. Similar to operational efficiency, the direct operational expenses of felling and processing in the conventional operation system tended to increase according to the increased production volume per area, because it would be difficult to conduct processing operations by chainsaw efficiently in forests with more felled trees.

Although the direct operational expenses of bunching were similar between the conventional and mechanized operation systems, the operational efficiency of bunching in the mechanized operation system tended to be higher than in the conventional operation system because the machinery expenses for grapple loaders were significantly higher than those for mini-grapple loaders. In contrast to operational efficiency, the direct operational expenses of bunching were negatively correlated with road network density and were positively correlated with average pre-yarding distance. Similar to operational efficiency, the direct operational expenses of forwarding were expected to increase according to the increased average forwarding distance, but were not strongly correlated with average forwarding distance in our study.

Indirect operational expenses are listed in Table 7. The indirect operational expenses of the mechanized operation system tended to be lower than for the conventional operation system because overhead expenses decreased according to direct operational expenses, and the direct operational expenses of the mechanized operation system tended to be lower than for the conventional operation system. The machine transportation expense in Kurotasawa was significantly lower because the production volume was significantly higher.

**Table 7. Indirect operational expenses (USD/$m^3$)**

| | Site | Overhead | Log transportation | Machine transportation | Handling | Piling | Total |
|---|---|---|---|---|---|---|---|
| Conventional system | Azusa A | 16.39 | 13.00 | 0.31 | 8.75 | 6.94 | 45.39 |
| | Azusa B | 10.45 | 13.00 | 0.77 | 13.77 | 7.00 | 45.00 |
| | Nakanosawa | 17.51 | 13.00 | 0.76 | 16.94 | 7.00 | 55.20 |
| Mechanized system | Kurotasawa | 10.18 | 11.85 | 0.08 | 8.81 | 5.64 | 36.55 |
| | Shiroyama | 12.74 | 12.20 | 0.41 | 11.19 | 6.40 | 43.75 |
| | Kawanakako | 13.77 | 11.48 | 0.80 | 10.36 | 5.88 | 42.30 |
| | Yanome | 13.69 | 10.56 | 0.30 | 7.65 | 3.79 | 35.99 |

Operational expenses, including direct and indirect operational expenses, were 134.48 USD·$m^{-3}$ for Azusa A, 101.78 USD·$m^{-3}$ for Azusa B, 150.35 USD·$m^{-3}$ for Nakanosawa, 91.88 USD·$m^{-3}$ for Kurotasawa, 112.99 USD·$m^{-3}$ for Shiroyama, 117.16 USD·$m^{-3}$ for Kawanako, and 110.38 USD·$m^{-3}$ for Yanome. The operational expenses of the mechanized operation system tended

to be lower than for the conventional operation system. Operational expenses tended to be lower according to increased operation site area due to larger production volume.

Revenue and economic balance

The average unit price is listed in Table 4. The average unit price in Nakanosawa was higher due to its species of tree, Japanese cypress.

The economic balance was 12.07 USD·m$^{-3}$ for Azusa A, 99.92 USD·m$^{-3}$ for Azusa B, 65.56 USD·m$^{-3}$ for Nakanosawa, 33.06 USD·m$^{-3}$ for Kurotasawa, 64.24 USD·m$^{-3}$ for Shiroyama, 83.68 USD·m$^{-3}$ for Kawanako, and 51.49 USD·m$^{-3}$ for Yanome (Fig. 3). The direct operational expenses of the mechanized operation system tended to be lower than for the conventional operation system. However, revenue differed from one site to another due to stand conditions. Therefore, significant differences were not observed between the conventional and mechanized operation systems. The economic balances of all operation sites were positive. However, the economic balances without subsidies in Azasa A, Kawanakako, and Yanome were negative, even though there was a larger area and higher road network density in Yanome. This highlights the current situation in Japanese forestry, where thinning operations are almost pre-commercial, and large amounts of thinned wood are left in the forest.

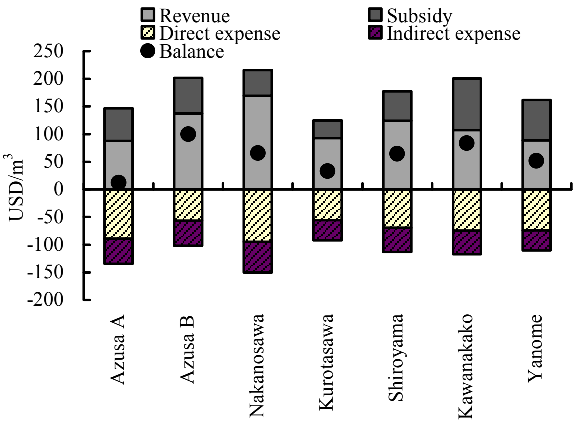


**Fig. 3 Economic balances**

## Discussion

Economic balance

The economic balance without the subsidy in Yanome was negative despite a larger area and higher road network density. Therefore, operational expenses were examined according to operation site area, road network density, and operation system with different average slope angles and stem volumes. Direct operational expenses were estimated using equations (Table 8, Nakahata et al. 2011). The equation to estimate chainsaw-felling expenses was related to average thinned wood volume. The equation to estimate chainsaw- and processor-processing expenses was related to average log volumes. The equation to estimate mini-forwarder- and forwarder-forwarding expenses was related to average forwarding distance. Average forwarding distances were estimated using Equ. 3 with operation site area. Direct operational expenses of strip road establishment $C_R$ (USD) were estimated using strip road length $L$ (m) from operational efficiency in length and hourly operational costs.

$$C_{RC} = 2.70L \quad \text{for the conventional operation system (4)}$$

$$C_{RM} = 3.02L \quad \text{for the mechanized operation system (5)}$$

Strip road length was estimated using areas and road network density using Equ. 2 with average slope angle. Using these equations enabled us to examine operational expenses according to operation site area, road network density, and operation system.

Area

Larger areas would be expected to improve operational efficiency and reduce costs because forest road networks could be established effectively, and large forestry machines could be operated efficiently. Furthermore, larger areas had reduced fixed costs per volume, such as machine transportation expenses. However, larger areas have increased average forwarding distances and therefore forwarding expenses based on the equation used in this study. Therefore, 6 ha proved to be an appropriate operation site area with minimum operational expenses (Fig. 4). The areas with minimum operational expenses were the same even with different average slope angles. The areas with minimum operational expenses were different from one site to another due to site conditions. For example, Ishikawa et al. (2008) estimated the areas with minimum operational expenses as 2–5 ha in Fukui prefecture, Japan. However, the forest owners' cooperative in this region aggregated approximately 6 ha operation site areas and conducted forestry operations on aggregated sites (Table 1). Therefore, 6 ha would be an appropriate operation site area in this region. Furthermore, a new subsidy system was started in 2011, which provides subsidies for thinning operations with operational site areas greater than 5 ha and production volumes more than 10 m$^3$·ha$^{-1}$. Therefore, 6 ha is also an appropriate operation site area for the new subsidy system.

Forest road networks

Road network density was examined for areas with the same average slope angle (Fig. 5) and different average slope angles (Fig. 4). Road network density was estimated using equation (2) with average slope angles. Road network density was estimated as 316 m·ha$^{-1}$ for 5°, 290 m·ha$^{-1}$ for 10°, and 269 m·ha$^{-1}$ for 15°. Higher road network density increased operational expenses due to the higher direct operational expenses of strip road establishment. Therefore, road network density should be reduced to approximately 200 m·ha$^{-1}$ within the average pre-yarding distance on which a grapple loader could conduct bunching without

winching, although the road network density tended to be higher on slopes with gentle angles. Ishikawa et al. (2008) also estimated the road network density with minimum operational expenses as 330 m·ha$^{-1}$, so that bunching could be conducted without winching.

**Table 8. Equations used for estimating direct operational expenses**

| System | Machine | Operation | Efficiency (m$^3$/person-hour) | Direct expense (USD/m$^3$) | Reference |
|---|---|---|---|---|---|
| Both | Chainsaw | Felling | $3,600Vn/(136Vn + 111)$ | $0.53/Vn + 0.65$ | Nakahata et al. 2011 |
| Conventional | Chainsaw | Processing | $3,600Vl/(690Vl + 81)$ | $0.39/Vl + 3.29$ | Nakahata et al. 2011 |
| Conventional | Mini-grapple loader | Bunching | 1.8 | 14.36 | Nakahata et al. 2011 |
| Conventional | Mini-forwarder | Forwarding | $8,928/(1.10L_F + 1,660)$ | $0.0074L_F + 11.13$ | Nakahata et al. 2011 |
| Mechanized | Grapple loader | Bunching | 4.7 | 11.99 | Nakahata et al. 2011 |
| Mechanized | Processor | Processing | $3,600Vl/(89Vl + 114)$ | $2.46/Vl + 1.92$ | Nakahata et al. 2011 |
| Mechanized | Forwarder | Forwarding | $15,804/(1.50L_F + 1,236)$ | $0.0064L_F + 7.08$ | Nakahata et al. 2011 |
| Conventional | Mini-grapple loader | Bunching | $(0.034d + 7.58)/6$ | $231.12/(0.034d + 7.58)$ | This study |
| Mechanized | Grapple loader | Bunching | $(0.041d + 17.03)/6$ | $415.80/(0.041d + 17.03)$ | This study |

$Vn$: Thinned wood volume (m$^3$/stem), $Vl$: Log volume (m$^3$/stem), $L_F$: Forwarding distance (m), $d$: Road network density (m/ha)

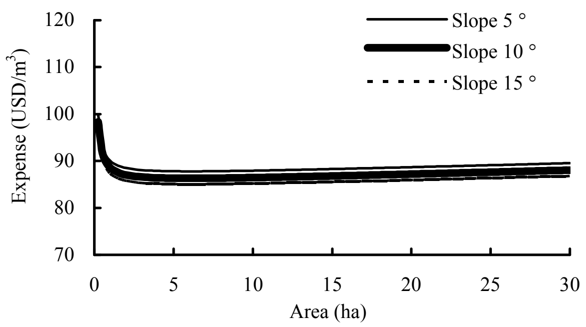


**Fig. 4 Estimated operational expenses with different average slope angles in Yanome**

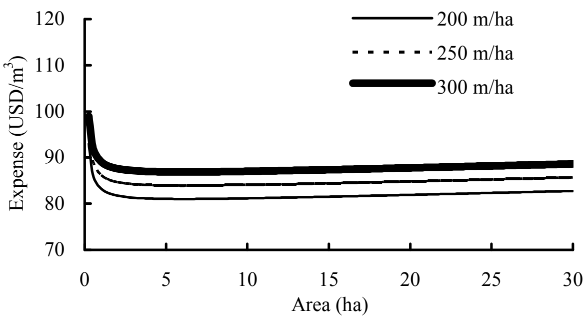


**Fig. 5 Estimated operational expenses with different road network densities in Yanome**

However, the direct operational expenses estimated using the equation in Table 8 (Nakahata et al. 2011) did not change according to road network density or average pre-yarding distance. In this study, the operational efficiency of bunching $P_B$ (m$^3$/person-day) was positively correlated with road network density and negatively correlated with average pre-yarding distance.

For the conventional operation system:

$$P_{BC} = 0.034d + 7.58 \quad (6)$$

For the mechanized operation system:

$$P_{BM} = 0.041d + 17.03 \quad (7)$$

Conversely, the direct operational expenses of bunching $C_B$ (USD·m$^{-3}$) were negatively correlated with road network density and positively correlated with average pre-yarding distance.

For the conventional operation system:

$$C_{BC} = \frac{231.12}{0.034d + 7.58} \quad (8)$$

For the mechanized operation system:

$$C_{BM} = \frac{415.80}{0.041d + 17.03} \quad (9)$$

Mini-grapple-loader and grapple-loader bunching expenses were estimated using Equ. 8 and Equ. 9 with road network density, and operational expenses were also estimated using these equations. Similar to the result above, higher road network density increased operational expenses, although the differences between operational expenses for different road network densities was smaller due to shorter bunching distances and subsequently lower bunching expenses.

## Mechanization

Operational expenses were estimated for the conventional operation system in addition to the mechanized operation system in Yanome. The operational efficiency and expenses of felling and

processing operations changed according to stem volume. Therefore, the effects of stem volume on operational expenses were also examined (Fig. 6 and Fig. 7). Larger stem volumes reduced expenses for both operation systems. However, a larger reduction occurred for the mechanized operation system. Conversely, with smaller stem volumes, 0.20 $m^3$/stem, the operational expenses for the mechanized operation system were higher than those for the conventional operation system. Therefore, the appropriate operation system and appropriate machine size should be selected according to stem volume. The areas with minimum operational expenses were different based on stem volume and operation system: 8.00 ha for 0.20 $m^3$/stem, 6.00 ha for 0.35 $m^3$/stem, and 5.00 ha for 0.50 $m^3$/stem for the mechanized operation system and 7.00 ha for 0.20 $m^3$/stem, 5.25 ha for 0.35 $m^3$/stem, and 4.50 ha for 0.50 $m^3$/stem for the conventional operation system. The areas with minimum operational expenses were reduced according to increased stem volumes (Ishikawa et al. 2008).

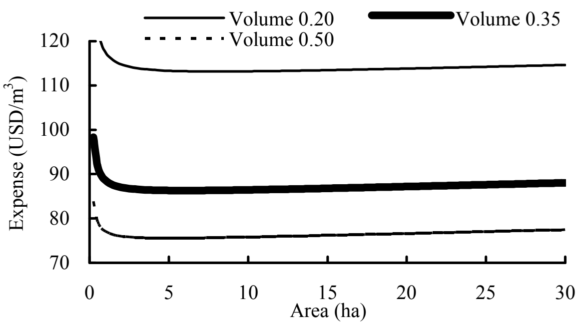


**Fig. 6 Estimated operational expenses with different average stem volumes for the mechanized operation system in Yanome**

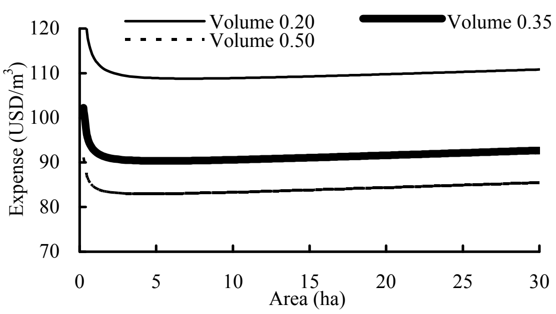


**Fig. 7 Estimated operational expenses with different average stem volumes for the conventional operation system in Yanome**

## Conclusions

Operational efficiency increased and operational expenses decreased according to the increased operation site areas using the mechanized operation system. However, road network density was not strongly correlated with operational efficiency or costs in the research sites of this study.

Some equations were developed in this study, for example, to estimate road network density with average slope angle, operational efficiency of bunching with road network density, and average forwarding distance with operation site area. Operational expenses were estimated using these equations and the area with the minimum operational expenses was 6 ha. The forest owners' cooperative in this region aggregated approximately 6 ha operation site areas and conducted forestry operations on the aggregated sites. Therefore, 6 ha is an appropriate operation site area in this region. However, there were few data available for this study, and the optimal area would probably differ from one site to another. Therefore, more research must be conducted.

Higher road network density increased operational expenses due to the higher direct operational expenses of strip road networks. Therefore, appropriate road network density should be determined by planning forest road networks according to site conditions such as geography, soil, and stand conditions before forestry operations begin because road network density tended to be higher on more gentle slopes. With larger stem volumes larger reduction of operational expenses occurred for the mechanized operation system compared to the conventional operation system. However, with smaller stem volume, the operational expenses for the mechanized operation system were higher than those for the conventional operation system. This study can help forest planers to select the appropriate operation system and appropriate machine sizes according to stem volume while considering economic balance.

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